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DATA FOR THE STUDY OF FATIGUE PROCESSES UNDER STATIC STRESS

Fiziologiya nervnykh protsessov [Physiology of Nerve Processes], 1955, Kiev, Pages 377-388

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The problem of fatigue in human muscul.r effort has long attracted the attention of physiologists. By atigue is meant a temporary decline in work capacity due to the work itself, expressed in a loss of strength by the muscles, decline in the coordination of all motor mechanisms, and onset of functional insufficiencies in the cardiovascular, respiratory, and other systems serving the muscular activity. A characteristic sign of fatigue, known to everyone from his own daily life, is the reduction in the work capacity of the muscles participating in particular work. It is this phenomenon that has been the subject of our study. The problem of the mechanism of muscular fatigue has been studied now for more than a century, and is the subject of a very large number of references, but has not fully resolved to this day.

The study of fatigue mechanisms, primarily in isolated frog nerve and muscle specimens, the data from which were extrapolated to the human organism as a whole, and the highly mechanical analysis of the facts thus arrived at, have led to the wide dissemination in physiological circles abroad of primitive humoral theories of the localization of fatigue.

The initial hypothesis in the development of these localistic concepts was the seemingly sensible sense idea that if

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muscles display a decline in capacity for work, the reason must lie primarily in changes within these muscles themselves. However, a scientific examination of the question provides no foundation for this conclusion. Each voluntary muscular contraction is an action of the organism as a whole, participated in to begin with by cortical and subcortical motor mechanisms, numerous receptors (particularly muscular) with their complex afferent systems carrying the flow of signals to the higher subcortical centers and, further, to the motor analysor of the cerebral cortex. Participating in this work are the internal organs providing the muscles and the nervous system with metabolism at the required level. Thus the full regulatory action of the internal organs of the cortical and subcortical centers participate. The work capacity displayed by the muscle at any moment is dependent upon the condition of all the links in this complex unitary system.

In 1903 I. M. Sechenov provided the foundation for understanding the leading role of the nerve centers in muscular fatigue. In experiments on his own body he found that the respiration of fatigued muscles is better -- not when other muscles are at rest -- but when they are active (the phenomenon of "active" rest). This can be explained only if one recognizes that it is not the muscles but the nerve centers which primarily undergo fatigue.

The ideas of Sechenov have been developed by a number of Soviet physiologists whose work has firmly rooted the concept of nervism in the knowledge of fatigue (L. L. Vasil'yev, M. E. Marshak, M. I. Vinogradov, A. A. Ukhtomskiy, D. I. Shatenshteyn, etc).

A most important problem of research in this field is the study of changes in the condition of the centers of nervous activity which govern the development of muscular fatigue.

Static stress is a very convenient base for the study of fatigue. While dynamic work is accompanied by a constant interchange of activity between antagonistic muscles and nerve centers in reciprocal relation with one another and mutually affecting each other, in static stress the constant work of specific muscles and centers of higher nervous activity induces special susceptibility to fatigue.

It is important to note that the question as to the nature of fatigue under static stress places the conflict between the central-nervous and humoral-localistic theories of fatigue in the sharpest contrast.

Accumulated data completely refute the principle hypothesis of the humoral-localistic theory of static fatigue. The facts also contradict the idea that static fatigue is peripheral in nature. In 1931 M. E. Marshak demonstrated that in total fatigue, when it was no longer possible voluntarily to sustain a load, tetanization of the motor point of the muscle permitted work to continue for an appreciable period of time.

G. P. Konradi, A. D. Slonim, and V. S. Farfel' in 1934 advanced the hypothesis of the primary role of the cortical link in the central mechanism of fatigue under static stress. This hypothesis is substantiated by experiments with variations in work capacity under hypnosis, and by a number of clinical observations. In 1935 S. V. Gol'man showed that in patients with paralysis or amputation of extremities, the imagining of work very quickly produced fatigue, with all its typical signs: a tired feeling in the (absent!) extremities, pain therein, etc. In 1953 V. V. Rosenblat noted that resistance to static stress is particularly lacking in patients with spastic paresis (i. e., in whom a cortical neuron has been injured). This concept finds complete theoretical justification in the teachings of I. P. Pavlov.

Fatigue is a unitary process involving all the components of the neuromuscular instrument. Cortical cells are the prime element in the development of fatigue.

What changes occur in cortical cells in fatigue? A. A. Ukhtomskiy, dealing with the central mechanisms of muscular fatigue, noted in his day that fatigue and inhibition must not be confused. However, as both these processes occur in pronounced fatigue, and since, according to him, the elements of fatigue proper and of inhibition are intertwined, the problem of the relation between them retains importance.

In 1951, V. V. Rosenblat demonstrated experimentally that if an indifferent stimulus (a metronome) be coordinated with a period of active rest (other muscles functioning while one hand rests), it subsequently becomes possible to induce Sechenov's phenomenon of increased work capacity by means of the conditioned stimulus alone. These data have confirmed the role of cortical mechanisms in the phenomena under study, and have demonstrated that conditioned reflexes are capable of significantly affecting the course of the processes of fatigue and rest. Further, we undertook to connect an indifferent stimulus with the various phases of fatigue and, by studying its effect on work capacity, to get an idea of the nature of the processes proceeding in the motor analysor as fatigue develops.

We have run 3 series of researches on which we make a general report in the present article. More than 900 observations were made, on 25 subjects (students at the Medical School).

In the first series of researches — those for orientation — we attempted to coordinate an indifferent light stimulus (the lighting of a 40-w bulb in front of the subject) with the processes developing during the period of increasing fatigue, and then to determine the effect this stimulus had on work capacity.

Method

The working instruments were a standard mercury dynamometer and a portable appliance built in our laboratory in 1953 by V. V. Rosenblat. The constant stress consisted of compression of the dynamometer bulb by the wrist. The subject, having determined his maximum strenght, maintained the mercury column in the dynamometer at 1/2 that level by visual control. He continued to perform this work until no longer able to do so, meanwhile indicating the moment when the feeling of fatigue set in. When the work was done he rested for 1 1/2 minutes, whereupon he repeated the work at the previous level until no longer able to do so. As a result, we obtained 3 indices of work capacity: (1) endurance in seconds (duration of the first period of work); (2) time when the sensation of tiredness appeared (in seconds from the start of work), and (3) index of recovery (duration of second period of work after the 1 1/2-minute rest period, in percentage of the duration of the first period).

The conditioned connection was developed as follows. During each work period, when the subject reported the feeling of tiredness, we cut in a light stimulus which functioned for the remainder of the work period. Thus, application of the stimulus coincided in time with increasing fatigue, which ultimately compelled cessation of work. Preliminary observations showed the given stimulus to be indifferent as far as its effect upon work capacity is concerned.

Four subjects were used. Over a 2-month period they participated in 4 to 5 tests per week, producing 70 to 80 combinations in toto.

As to the method of developing the temporary connection, the following is of importance.

1. The experiments were performed in the ordinary environment of the laboratory. The subjects were not isolated from the experimenter and from other subjects (usually 2 subjects were present at a time, one of whom helped the researcher). We used this arrangement intentionally, so as to bring the experiment as far as possible into line with the conditions surrounding normal human muscular activity.

2. We did not eliminate the participation of our subjects' second signal system from formation of the temporary bond, as we believed the second signal system had to be actively involved in the development of the temporary connection, in order to enable the subject to be specifically conscious of the fact that the stimulus began to operate precisely in the period of rising fatigue. The second subject, assisting the experimenter, was the

person who applied the stimulus when his partner reported the feeling of fatigue. The true purpose of the study was not known to the subjects. We requested them, as active participants in the research, to study the course of training for static endurance. The "training" experiments continued for up to 2 months, and the subjects gradually ceased to be interested in the stimulus which became a normal part of the environment.

3. In view of the simultaneous participation of more than one subject in the experiments, the formation of a conditioned connection might also occur on the principle of "actors and audience," formulated by M. P. Shtodin in 194.. The student assistant who in the following experiment himself became the subject actually "lived through" the experimental environment with his partner each time, and by turning on the stimulus thereby associated it once again with a given point in the performance of work.

4. Our experiments would appear to contradict "A. N. Krestovnikov's rule," in accordance with which a conditioned reflex is developed only if the indifferent stimulus precedes the reaction with which it is associated. In our case the stimulus coincided with a specific moment during the work. However, as the greatest effect of the stimulus is at the moment it is cut in, this being preceded by the development of marked fatigue, the given objection loses its validity.

At the end of the 2-month preparatory period, 3 series of test experiments were run, in which the stimulus was cut in either (1) at the very beginning of the first period of work, and before its conclusion (this serving to determine the effect of the stimulus on endurance and the time when fatigue appeared), or (2) only dur. g the 1 1/2-mir te ost between the 2 periods of work (this being used to study the effect of the stimulus on the course of the process of recovery), or (3) not at all for purposes of control, it being understood that the data of the second group of check experiments served as controls for the indices of endurance and fatigue.

What was revealed by the studies thus conducted?

One might have expected that the application of the stimulus during the period of increasing fatigue must reduce work capacity. But the fact w: that it raised all the indices thereof. Endurance increased 8.7% on the average, the time before onset of fatigue by 16.1%, and the process of recovery was speeded by 11.3% [see Note].

([Note:] The percentages were obtained by taking as 100% the mean f. ure for the given index in experiments in which no conditioned stimulus was applied, and expressing all findings in experiments with the given subject as percentages thereof. All the averages in which we were interested were deduced from the "relative data o: individual experiments" thus obtained. This eliminated from the averages, and from the error therein, the effect of differences in the absolute magnitudes of the indices from subject to subject.)

As the data for the individual subjects were comparable, there was no need to be concerned about the accidental character of the results obtained, even though the number of control experiments was not great (31).

In an effort to clarify these seemingly incomprehensible findings, we compared them to the observations of a collaboratrix of G. V. Fol'bort, A. V. Semernina, who reported analogous findings in 1949 and 1951 in studying the exhaustion of the salivary glands of an animal: a conditioning agent, coordinated with the period of increasing exhaustion of the gland, had a positive effect on its work.

How are these observations to be explained?

TABLE 1

EFFECT OF LIGHT, COORDINATED WITH PERIOD OF RISING FATIGUE, ON INDICES OF STATIC WORK CAPACITY (FIRST SERIES OF OBSERVATIONS)

Subjects	Without conditioning stimulus (A)			With conditioning stimulus (B)			B/A (%)		
	V	U	Recov.	V	U	Recov.	V	U	Recov.
G-n	85.2	30.8	60.0	86.0	32.5	54.1	101.0	105.6	90.3
D-ch	118.8	18.6	38.0	136.5	23.0	48.8	115.0	123.5	128.3
To-a	81.7	29.3	62.2	85.5	35.5	65.0	104.7	121.0	104.4
Me-a	81.0	40.0	62.1	97.0	45.0	73.6	119.8	112.5	118.5
Average	95.9	27.4	53.4	102.0	32.4	57.2	108.7	116.1	111.3

(Note. This, and the succeeding tables, adduce average data for particular subjects. V is endurance in seconds, U is the work time before onset of tiredness, Recov. is recovery in 1.5 minute in %. The data in the third column (B/A (in %) is obtained from the relative data for the various experiments.))

It appears to us that it is very fruitful to employ, in the analysis of these facts, G. V. Fol'bort's conception on conjugate processes of fatigue and recovery in a functioning organ.

This conception provides a satisfactory general basis in physiology for examination of concrete instances of fatigue. If we take into consideration the state of the cells in the motor analyses of the cerebral cortex in static stress, the following general picture emerges.

The cortical cells are possessed of a given "functional potential." Uninterrupted excitation thereof in static stress leads to gradual exhaustion of this potential. However, the exhaustion results in an increase in the processes of recovery, developing in the process of the work itself and compensating for the fatigue. The greater the fatiguo, the more intensive the compensatory processes. They remain incapable, however, of fully compensating for the rising exhaustion, and when the latter comes to be markedly predominant, a third process appears — defensive transmarginal inhibition, which, undergoing a gradual increase, ultimately results in cessation of work and an acceleration of the processes of recovery during the period of rest. Thus, the essence of the changes in the cortical cells in fatigue may be conceived, schematically, as a complex interaction of 3 processes: exhaustion of functional potential, with recovery arising as a reaction thereto, and, finally, inhibition. The external picture of fatigue at any given moment is governed by the relation among these processes.

Our data may be explained as follows. The light stimulus, coinciding with the period of rising exhaustion, is related primarily to the processes of recovery which undergo intensive development at this time. This conditions the positive affect which our stimulus has begun to have on all the indices of work capactiy.

To verify the results of the first series of investigations, we undertook a second series, with 11 subjects. The conditioned stimulus used on this occasion was an aural agent: the sound of water flowing from a tap. Special experiments (73 observations on 6 subjects) demonstrated that this more powerful stimulus was indifferent in its effect upon work capacity. The method of work was the same as in the first series. The only difference was that, in view of the fact that the stimulus was more powerful, we believed it possible to reduce the number of combinations in the preparatory period to between 40 and 60.

Control observations (Table 2) have shown that 8 of 11 subjects yielded the same data as in the prior study: the stimulus applied during rising fatigue elevated all the indices of work capacity. This principle was clearly observed both in individual persons under test, and in the general mean data. Three of the persons under test yielded different results, and we shall return later to their analysis.

Thus, our second study generally confirmed the facts earlier revealed, which may also be explained by the conceptions of G. V. Fol'bort.

In the third series of studies we attempted to combine an indifferent stimulus — the sound of water — with the period of rest after static stress. The order in which the experiment was performed was the same as before, but the stimulus was cut in at the moment of cessation of work and continued to function during the first minute of recovery. 25 to 60 combinations were run with each of 10 subjects.

The data of the control observations (Table 3) again seem unexpected. The conditioning agent coinciding with the period of intense restorative processes should apparently raise all the indices. But in fact its effect was complex. Resistance and the period of work prior to the appearance of fatigue declines (on the average by 6.0 and 5.8%, respectively, while recovery increases markedly (by 12.1%). Although it was not possible to carry out control observations, so that accidental deviations cannot be excluded, the data for individual subjects fundamentally reiterated the principle common for the group average (in 7 of 9 persons, the conditioning stimulus had a more favorable effect on recovery than on other indices). This testifies the reliability of the results obtained.

If we now return to the "atypical" findings in the previous series, we see that 2 of the 3 subjects (A-a and Ta-a) show the same combination: the conditioning agent has, in general, a negative effect on the indices of endurance and fatigue, but a positive effect on recovery.

How is this explained? Does it not contradict the conjecture we have put forth? Thoughtful examination of these data show that, on the contrary, they confirm and deepen these conjectures. For these new data lead to the conclusion that the stimulus, applied at the moment of completion of work and functioning during the first minute of rest, entered into a relation primarily with the process of transmarginal inhibition which compels cessation of work. I. P. Pavlov called attention to the possible formation of such connections when he wrote: "If indifferent stimuli reach the cerebral cortex when an inhibitory process is dominant there, they chronically acquire an inhibitory function, i. e., when they later act upon the active points of the cortex, their effect is to induce an inhibitory process there" (<u>Collected Works</u>, Vol 4, 1947, Page 99).

TABLE 2

EFFECT OF AURAL CONDITIONING STIMULUS, APPLIED DURING RISING FATIGUE, ON INDICES OF STATIC WORK CAPACITY

(SECOND SERIES OF OBSERVATIONS)

Subjects	Without conditioning stimulus (A)			With conditioning stimulus (B)			B/A (%)		
	V	U	Recov.	V	U	Recov.	V	U	Recov.
Group One:									
Kh-a	77.3	50.0	76.8	79.8	56.0	84.2	103.1	112.0	109.7
K-ya	57.5	36.0	67.3	65.0	39.0	86.0	113.0	108.0	128.0
Ko-a	51.8	21.5	55.8	49.5	25.0	75.0	95.5	116.3	134.3
Ku-a	52.5	11.0	-	62.0	16.5	-	118.1	150.0	-
G-k	66.0	27.5	52.9	64.0	38.5	61.2	97.0	139.5	115.5
V-a	94.7	54.5	67.0	105.7	60.7	70.0	111.6	111.2	104.4
So-r	50.7	25.3	68.7	63.0	50.0	79.6	124.3	197.0	115.8
St-v	110.8	76.2	61.5	122.7	90.0	69.3	110.7	118.0	112.8
Group Two:									
A-a	86.8	58.0	60.7	84.3	51.7	69.5	97.7	89.0	114.5
I-a	72.5	28.3	68.9	74.0	20.0	64.8	102.0	69.5	93.3
Ta-a	64.0	23.5	62.5	54.5	24.0	64.9	85.3	102.0	103.8
Average	73.9	39.6	63.4	80.0	47.8	71.7	104.2 ±3.1	115.5 ±5.6	112.4 ±5.0
Average, Group I	73.1	40.6	63.5	82.4	51.4	74.2	107.6 ±3.8	123.9 ±6.0	116.3 ±5.4

Integral of probability (reliability of difference between data for Group One under effect of stimulus, and control data)

0.8501 0.9996 0.9793

TABLE 3

EFFECT OF AURAL CONDITIONING STIMULUS, APPLIED AT END OF WORK AND DURING FIRST MINUTE OF REST, ON STATIC WORK CAPACITY

(THIRD SERIES OF OBSERVATIONS)

	Without conditioning stimulus (A)			With conditioning stimulus (B)			B/A (%)		
	V	U	Recov.	V	U	Recov.	V	U	Recov.
M-v	96.2	57.2	57.5	82.0	50.5	79.4	85.2	88.3	137.8
Ch-kh	75.2	59.7	62.0	73.5	57.0	68.5	97.8	95.3	110.3
S-r	78.0	50.0	46.0	76.0	50.0	49.9	97.5	100.0	108.5
S-v	84.0	60.0	79.7	72.5	52.5	73.9	86.3	87.5	92.5
Kh-n	106.0	83.3	77.0	96.0	71.0	55.0	90.5	85.0	71.5
V-v	121.0	82.2	43.0	126.0	80.0	46.2	104.0	97.5	107.0
R-y	76.5	48.5	61.0	70.0	48.0	58.0	91.5	99.0	95.0
I-a	76.2	45.5	53.5	79.0	51.0	75.1	103.5	112.0	140.3
M-v	79.7	67.2	58.2	82.0	64.0	68.5	102.7	95.0	117.5
Average	86.9	61.2	58.6	82.1	57.0	65.8	94.0 ±2.4	94.2 ±2.4	112.1 ± 5.5
Integral of probability (reliability of difference between data under effect of stimulus, and control data)							0.9357	0.9412	0.9676

If, as we see, our conditioning stimulus related to the process of inhibition, its effect became understandable. Recovery increases, as recuperative processes are known to accelerate as inhibition rises. Endurance declines, as the transmarginal inhibition, which brings work to an end, increases more rapidly. As tiredness also sets in more rapidly, the conclusion is possible that the sensation of an internal obstacle and the desire to stop work, which is called tiredness, is a reflection of transmarginal inhibition developing in the motor analyser. Thus it may be supposed that the subjective phenomenon of fatigue (the sensation of tiredness) has the process of inhibition as its objective basis.

On comparison of all the foregoing data the following question arises: if 3 fundamental processes (exhaustion, recovery, and inhibition) interact in the cortical cells in the presence of fatigue, why do stimuli corresponding with the various phases of work enter into a relation primarily with 2 of these processes? In examination of the literature we find in this regard as well data analogous to our own. Thus in 1951 A. O. Dolin reported that he readily produced a conditioned-reflex catalepsis, while it was exceedingly difficult to induce an epileptic fit by conditioned reflex. His analysis of these facts led him to the conclusion that thanks to the "protective tendencies of the nervous system," the production of an elaborate complex of changes in the organism by the conditioned-reflex route causes processes of a defensive character to predominate. As the processes of recovery and inhibition are reflex reactions of the cortical cells to exhaustion, the conditioned stimuli enter into relation primarily with these defensive processes.

Concerning the questions as to why our stimuli under various circumstances are connected now with one, now with another process, analysis of the conditions of experiment makes this matter quite clear. When we coordinated an indifferent agent with the period of rising exhaustion, the cutting in of the stimulus (which is, as known, the moment of its greatest effect) coincided with the moment when the restorative processes were intensively at work, while inhibition ... [illegible] to appear (the subject had only begun to feel tired). Therefore, the conditioning agent related primarily with recuperation. However, when we combined it with the first minute of rest, cutting it in coincided with the moment of cessation of work, i.e., with the maximum development of transmarginal inhibition. This led to the stimulus forming a connection primarily with the latter process. In individual subjects ("atypical" data in the second series) the stimulus accompanying rising exhaustion formed the connection with inhibition. These differences may perhaps be conditioned by typological peculiarities in the individuals concerned.

The experimental and literature data adduced permit the following conclusions on the mechanism of exhaustion in static stress.

The exceptional fatigue-producing capacity of the type of work in question is related to the uninterrupted excitation of the given nerve and muscle instrument. This has a negative effect on all links in the motor apparatus, from the muscles to the higher nervous centers, cortical cells being most subject to fatigue. They carry a heavy load in processing the proprioceptive impulses from the muscles under stress and in elaborating, in indissoluble unity with these signals, cortical voluntary impulses governing contraction. Finally, powerful streams of excitation of the chemoreceptors in muscular tissue, which are specially sensitive to lactic acid in particular (V. M. Khayutin, 1953), move to the cortex, and in this sense biochemical changes in working muscle may have a substantial effect upon fatigue. The continuity of the streams of excitation moving to and away from the cortical conditions and their rapid exhaustion conditions, discoordination of all the processes related to work and also, most probably, direct suppression of the functions of the peripheral apparatus, by changes in their excitability and trophics. Thus, fatigue is a complex process of primarily cortical mechanism.

In fatigue a complex interrelation of a series of processes occurs in the cells of the motor analysor.

The state of function of the cortical cells, revealed at the level of their lability, is determined in the process of work by the relationship between the processes of exhaustion of the functional potential (G. V. Fol'bort), and the occurrence, as a reaction to this exhaustion, of the processes of recovery and, finally, of transmarginal inhibition. At the beginning of work, the processes of exhaustion are compensated for by restorative processes. As exhaustion proceeds, due to the constant flow of excitation of the working cells, the processes of recovery also become more intense. When exhaustion increases to the point that it is inadequately compensated for by these processes, an inhibitory process appears. This compels the worker to apply a greater effort of will to overcome the developing internal obstacle, this being felt subjectively as tiredness in the muscles. Subsequently, the increasing exhaustion, on the one hand, and the developing inhibition on the other, increasingly reduce the lability of the cells becoming fatigued, with the result that it finally declines to zero, causing the work to become a negative stimulus, whereupon a parabiotic inhibition, stopping the work, arises in the corresponding portion of the motor analysor. Thus, 2 phases may be distinguished in the mechanism of cortical fatigue. First the work capacity declines in connection with the increase in exhaustion of the functional potential. Subsequently, transmarginal inhibition is connected therewith and it further reduces work capacity in the form of a defense reaction.

It is clear from the foregoing that it would be an error to identify inhibition with fatigue. Inhibition is but one of the components in the total picture of fatigue, and results from exhaustion of the cortical cells.

These, then, are the conclusions to which the results of our experiments lead.

Of course, our data are limited as yet, and may only be regarded as a first effort to use conditioned reflexes in the study of the intimate nature of the processes of exhaustion and rest. However, it would appear to us that this effort demonstrates the fruitfulness of this line of research. Investigations in this direction are not only of theoretical interest, but may also be of practical value, as the facts we have derived demonstrate that various stimuli, accidentally or causally coinciding with specific phases of muscular work, are capable of exercising a pronounced effect upon working capacity by the conditioned reflex route. This presents the possibility of opening new perspectives in the direction of combatting fatigue in production and athletics. Further elaboration of this question may therefore offer much of value both to theory and practice.